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FRACTURE TOUGHNESS EVALUATION OF DUCTILE MUNITIONS MATERIAL

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It has been difficult to obtain fracture toughness data from actual artillery projectiles due to the stringent size requirements imposed by linear elastic fracture mechanics. This difficulty could be alleviated by an elastic-plastic stress analysis to determine the fracture toughness. The J-integral offers the most promising solution to this problem.

Before applying the J-integral to projectile problems, one must determine if the results of the J-integral will be equivalent to those obtained from

20. (Cont'd)

the standard K-test using projectile steel. The material chosen for this study was 1340 steel heat treated to 1035 MPa (150,000 psi) yield strength. The K_{I_c} of this material was previously determined using 0.1016m (4 in.) thick CKS specimens and the test conformed to all the ASTM requirements.

The J value was determined by the single specimen techniques. Good agreement was observed between the K_{I_c} value and J_{I_c} value after converting it to K. Some effect of crack length on J was observed.

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INTRODUCTION

In the past, it has been difficult to obtain fracture toughness data directly from many armament items such as rocket motors or thinwalled shells. The information sought has been obtained from rolled plate or forgings which may have different metallurgical properties. In addition, if the item was fabricated from ductile material, the problem was compounded by the strigent size requirements imposed by linear elastic fracture mechanics. It is essential, therefore, to be able to determine the fracture toughness using a method which can allow for some plasticity in the specimens during testing. Such a test method would permit machining test specimens directly from the item being investigated and using smaller specimens for tests of ductile materials.

The J integral as proposed by Rice (ref. 1, 2) offers the possibility of extending the concepts of fracture mechanics into the plastic flow area. Here J is a path independent integral and can be defined as:

$$J = \sum P_i \frac{d\Delta i}{dA} - \frac{DU}{dA} T$$

Where P_i is one of the applied loads

Δ_i is the corresponding load displacement

dA is an infinitesimal increment of new servered area

U_T is the total strain energy of the body containing the crack.

In the elastic region the expression for G and J are identical.

Some preliminary experimental investigations directed toward developing experimental procedures have been reported by the Westinghouse Electric Corporation Research Laboratories, Del Research Inc., and the University of Illinois (ref. 3, 4, 5). Before applying this new concept to Army problems, however, a suitable test method must be developed. The material used in this development should possess mechanical properties similar to the projectiles to be projectiles to be investigated, and the fracture properties should be established using a standard test method

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APPROACH

To explore the use of the J integral for determining the fracture toughness of projectile materials, small specimens suitable for the J integral investigation were machined from material having a known valid fracture toughness. These specimens were then tested to determine the J value, which was converted to K. The fracture toughness values so determined were compared.

EXPERIMENTAL PROCEDURE

Materials

The material selected for this phase of the investigation was 1340 steel heat treated to approximately 1035 MPa (150,000 psi) yield strength. Two heat treatments were employed to attain this yield strength. One heat treatment was developed to produce a structure of tempered martensite, and the other was developed to produce a structure of tempered martensite and bainite.

This material was originally tested as 0.1016m (4 inch) thick Compact K Specimen (CKS). The plane strain fracture toughness values obtained were valid according to all criteria proposed by American Society for Testing and Materials (ASTM) committee E24. CKS specimens 0.0254m (1 in.) thick were machined from the broken halves of the large specimens for the J testing.

Methods

The tests were conducted using an Materials Testing System (MTS) servo-controlled, hydraulic, closed-loop mechanical test machine of 44,480 N (10,000 lbs) capacity. A PDP-8-E computer and interface provided a means of recording and storing load and displacement data for subsequent playback. A double cantilever clip-in displacement gage provided a linear, accurate and sensitive means of crack-opening-displacement measurement.

The specimen selected for this investigation was a 0.0254m (1 in.) CKS specimen precracked to $\frac{a}{w}$ of approximately 0.75.

The tests were conducted at a cross-head speed of 0.0015 m/min (0.06 in./min). In order to distinguish small changes in specimen compliance (indicative of a change in crack length), an analog signal proportional to the applied load was subtracted from the load-line displacement signal such that the linear portion of the load displacement curve was vertical. When the specimen was partially unloaded (about 10% of P_{max}), the elastic behavior of the specimen was restored and could thus be used for determining crack extension. Up to 1500 data points of load and load-line displacement were stored for playback on the X-Y recorder.

To compute J, the area under the load verses load-line displacement is used according to the relationship

$$J = \alpha_1 \frac{2A}{Bb} + \alpha_2 \frac{2P}{Bb}$$

Where

P = Load

δ = Load-Line Displacement

A = Area Under Corrected P-δ Curve

B = Specimen Thickness

b = Remaining Ligament

α_1, α_2 = Merkle-Curtin Coefficients

The values of J verses Δa was plotted for each unload slope. The change in crack length, Δa, was computed using the following relationship:

$$\Delta A_m = \sum_{i=1}^{i=m} \frac{b - \Delta A_i - 1}{2} \cdot \frac{C_i - C_{i-1}}{C_i - 1} \cdot f \frac{a}{w}$$

C = Specimen Compliance

$$f(\frac{a}{w}) = -1.89878 + 12.6561(\frac{a}{w}) - 20.9371(\frac{a}{w})^2 + 14.6380(\frac{a}{w})^3 - 3.45833(\frac{a}{w})^4$$

The remaining ligament length in addition to the final Δ a measurement is based on the average of nine equally spaced measurement points across the fracture surface.

RESULTS AND DISCUSSION

A typical load verses load-line displacement curve is shown in figure 1. The unloading points used in calculating the J verses Δ a curve readily discernable.

The J verses Δa curves for 1340 steel in the tempered martensite condition are shown if figures 2 and 3. In these figures, J is plotted as a function of Δa. The curve marked $\Delta a = {}^{J}/2\sigma y$ is the blunting line. The intersection of the blunting line and the best fit straight line drawn through the remaining points is the operational J_{Ic} as difines by ASTM Committee E24. Notice that the J_C (J_{Ic}) determined for specimen M1 is much greater than the values determined for specimen M2. This effect will be discussed later.

The experimental data for the 50 percent tempered martensite-50 percent bainite structure are shown in figures 4 and 5. The same analysis was applied here as in the preceeding example. The agreement for the J_C values in this case is quite good, and experimental data are summarized in table 1.

One will observe that the experimental results for speciments M1 and M2 differ by approximately 21190 $\frac{Nm}{m^2}$ (100 in. lbs/in.). This discrepancy is greater than anticipated or desired, however, attention is directed to the length of the unbroken ligament. The length of the unbroken ligament in M1 is greater than the length of the unbroken ligament in M2. Apparently this results in a steeper slope for J versus Δ a curve (figures 2 and 3), with a higher intersection point with the blunting line in determining J_C. This behavior needs additional study to make sure one is measuring a material property.

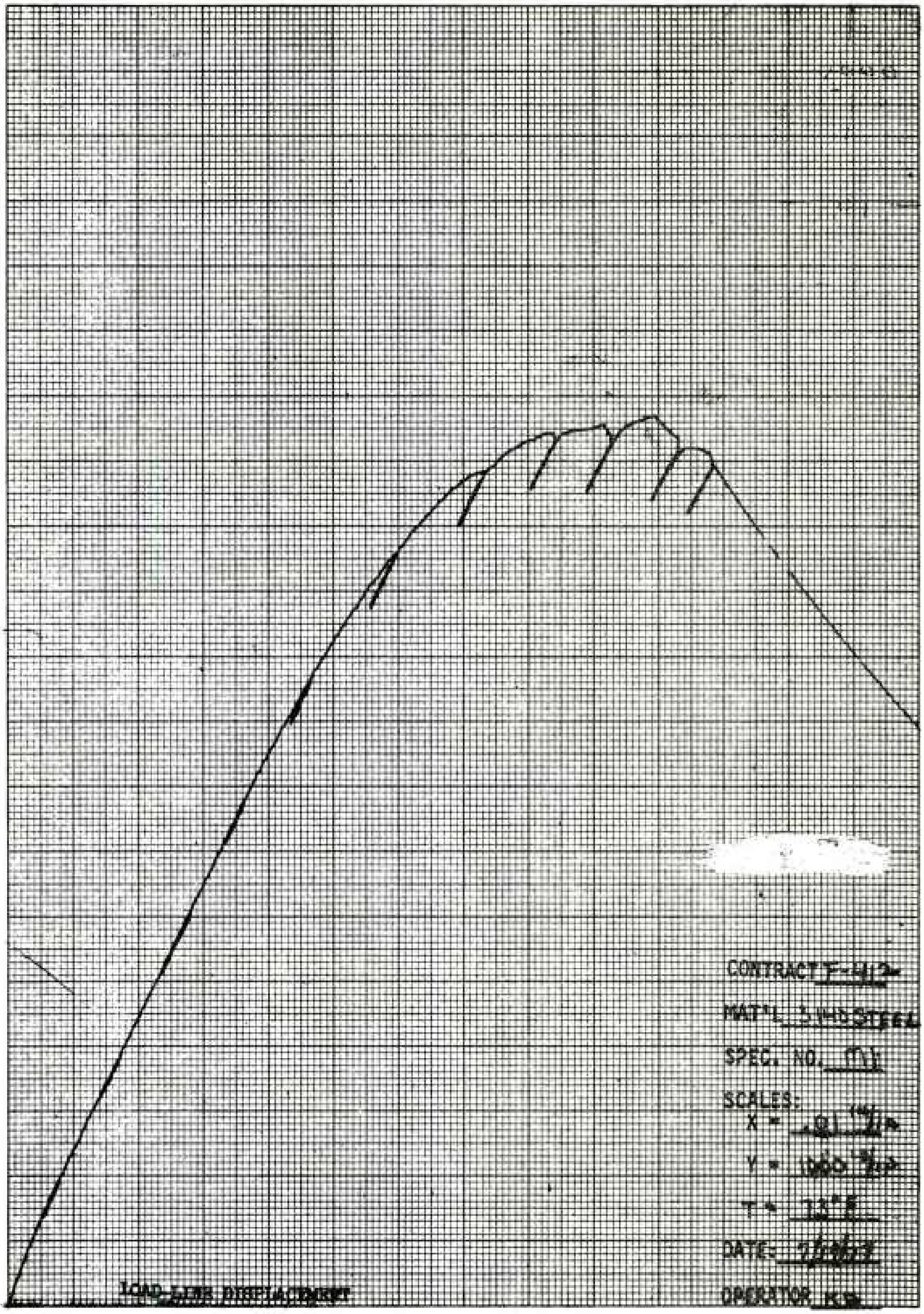

Figure 1. Load-line displacement curve of specimen M1.

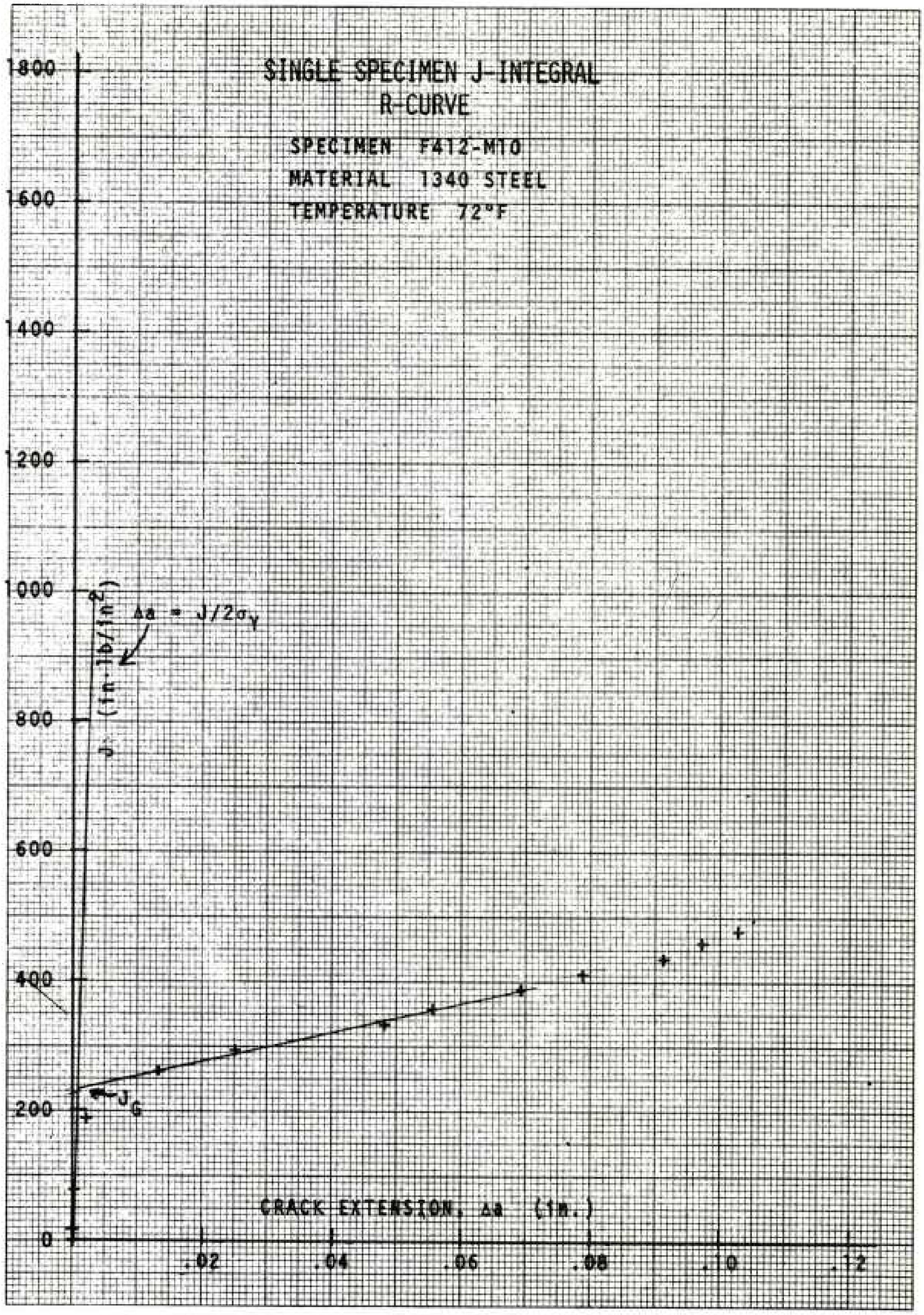

Figure 2. J_R (J vs Δa) curve for specimen M1 (long unbroken ligament).

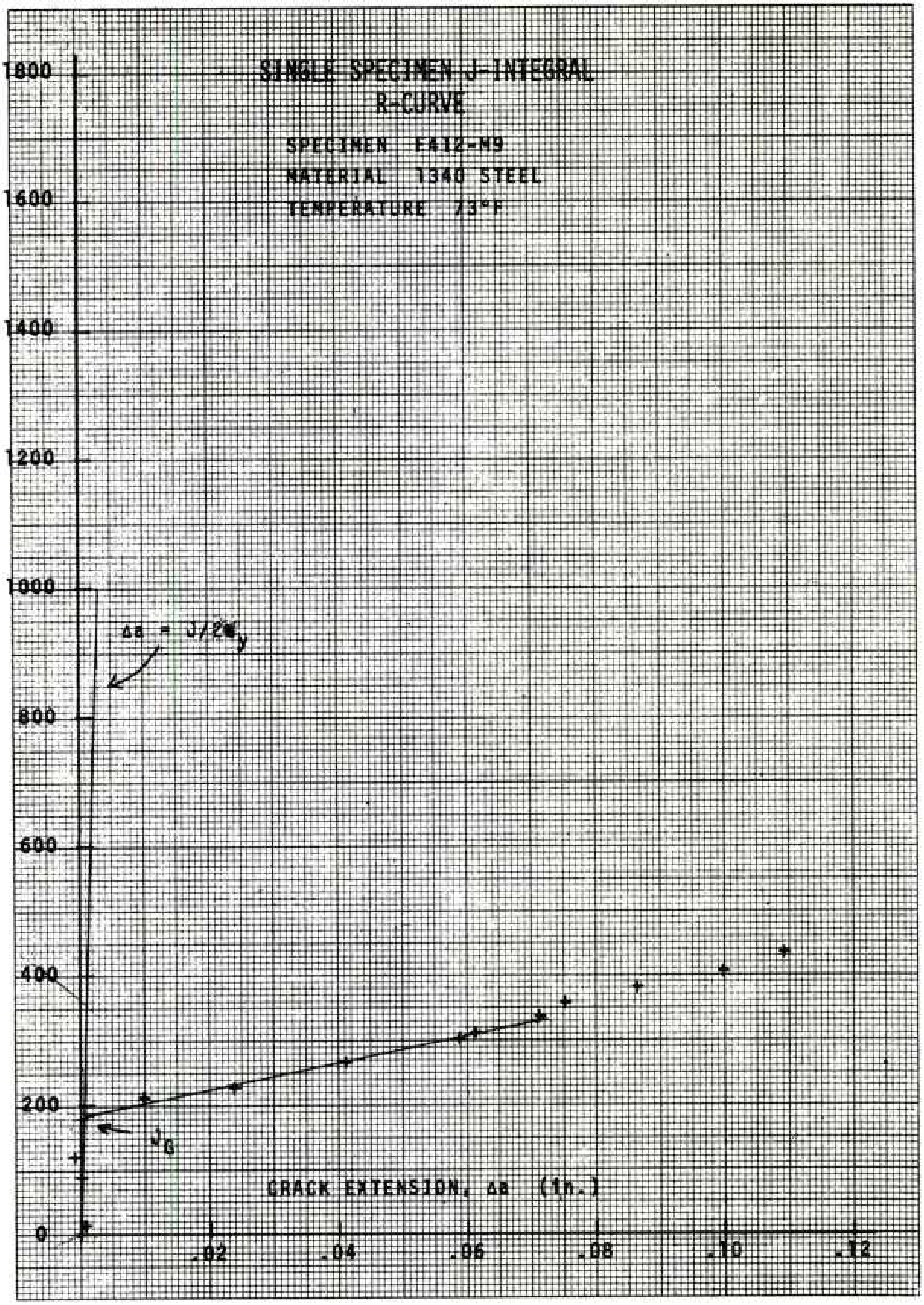

Figure 3. J_R curve for specimen M2 (short unbroken ligament).

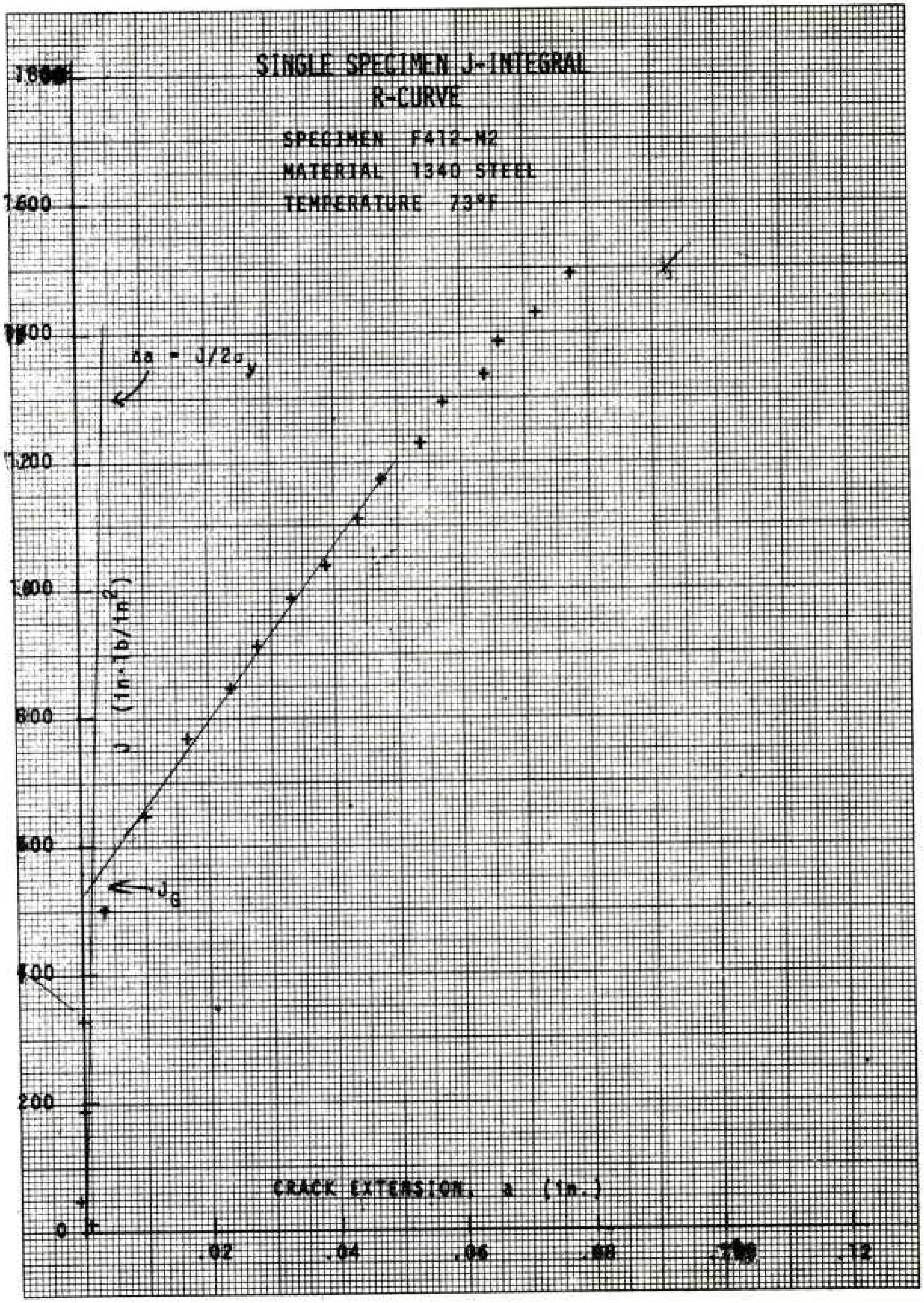

Figure 4. J_R curve for specimen M9.

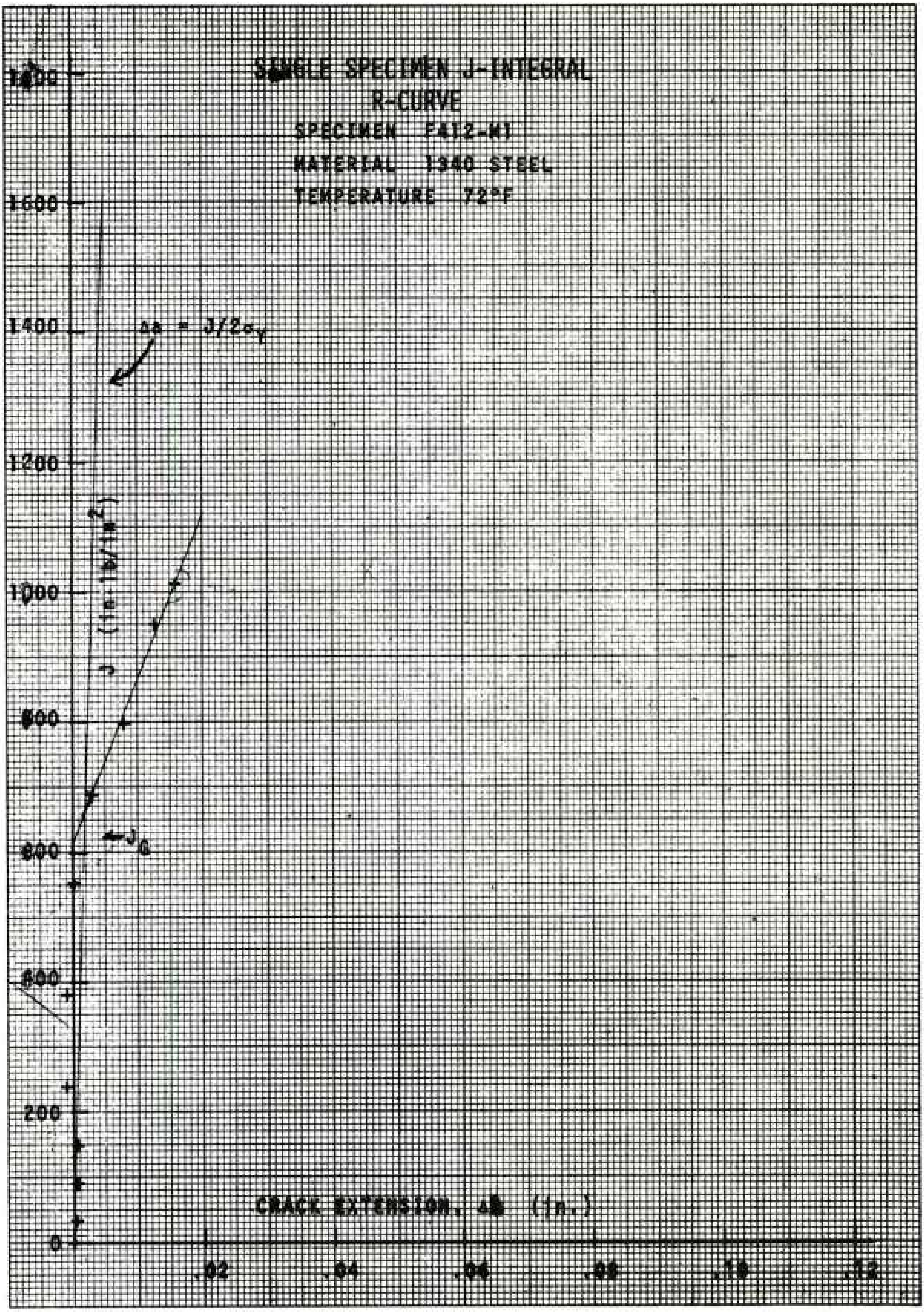

Figure 5. JR curve for specimen M10.

Table 1. Summary of J data[4] for 1340 steel

Structure	Spec No.	B (in.)	W (in.)	b_o[1] (in.)	b_f[2] (in.)	J Instab[3] (in. lbs/in.^{2})	K Instab (ksi$\sqrt{\text{in.}}$)	J_G (in lbs/in.^{2})	K_G (ksi$\sqrt{\text{in.}}$)
Temp Mart	M1	.975	2.000	.559	.513	902	165	644	141
Temp Mart	M2	.974	2.000	.467	.310	674	139	544	128
Mart & Bainite	M9	.975	1.999	.467	.293	212	80	185	76
Mart & Bainite	M10	.976	1.000	.459	.312	253	87	233	84

1. b_o = initial unbroken ligament

2. b_f = final unbroken ligament

3. Instability is defined as the firse decrease in applied load.

4. Refer to the appendix for a table of metric equivalents.

On the other hand, the unbroken ligaments in specimens M9 and M10 are essentially the same, and the J values agree reasonably well with each other. The specimen dimensions were adequate to obtain valid J values.

Comparison of the J data ($K= \ EJ$) with the K data obtained using the 0.1016m(4 in.) thick specimens shows that the J value at instability corresponds very closely with the K_{Ic} data. The J_G data show a somewhat lower value of fracture toughness when compared with the 0.1016m (4 in.) thick test. However, these results are conservative.

CONCLUSIONS

Some conclusions are:

1. The value of J at instability corresponds very closely with the value of fracture toughness determined using 4-inch thick CKS specimens.

2. The value of J_G determines using the J versus Δa curve is conservative.

3. The shape of the J versus Δa curve is influenced by the length of unbroken ligament - the longer unbroken ligament-resulting in a steeper slope and a greater value of J_G.

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APPENDIX. TABLE OF METRIC EQUIVALENTS

1 in. = 0.0254m
2 in. = 0.0508m
4 in. = 0.1016m

1000 lbs = $4.448X10^3N$
2000 lbs = $8.896X10^3N$
5000 lbs = $22.240X10^3N$
10000 lbs = $44.480X10^3N$

50 ksi $\sqrt{\text{in.}}$ = .05535 M Pa · m 1/2
100 ksi $\sqrt{\text{in.}}$ = .1107 M Pa · m 1/2
150 ksi $\sqrt{\text{in.}}$ = .1660 M Pa · m 1/2
200 ksi $\sqrt{\text{in.}}$ = .2214 M Pa · m 1/2

100 in. lbs/in.^{2} = 21192 N · m/m^2
200 in. lbs/in.^{2} = 42385 N · m/m^2
400 in. lbs/in.^{2} = 84771 N · m/m^2
800 in. lbs/in.^{2} = 169542 N · m/m^2
1000 in. lbs/in.^{2} = 211929 N · m/m^2

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